

## Seasonal and interannual variability of calcite in the vicinity of the Patagonian shelf break (38°S–52°S)

Sergio R. Signorini,<sup>1</sup> Virginia M. T. Garcia,<sup>2</sup> Alberto R. Piola,<sup>3</sup> Carlos A. E. Garcia,<sup>4</sup> Mauricio M. Mata,<sup>4</sup> and Charles R. McClain<sup>5</sup>

Received 14 April 2006; revised 29 June 2006; accepted 7 July 2006; published 23 August 2006.

[1] The timing and duration of coccolithophore blooms along the Patagonian shelf break, as well as insights on the mechanisms that drive and maintain these blooms, were analyzed using time series of chlorophyll chl *a*, calcite, and sea-surface temperature (SST) derived from remote sensing data (SeaWiFS and AVHRR) and historic hydrographic data. The seasonal variability and succession of phytoplankton groups respond to light intensity and nutrient supply within the mixed layer due to seasonal changes in stratification. The early spring bloom is diatom-dominated and starts in September under nutrient-rich Malvinas waters when the mixed layer begins to shallow (<80 m), and peaks around November with mixed layer depths (MLD) less than 40 m. After nutrient depletion from the spring bloom, a coccolithophore bloom begins in November when the MLD is less than 40 m, and peaks in January when the MLD reaches its minimum (18 m) and PAR reaches its maximum intensity. **Citation:** Signorini, S. R., V. M. T. Garcia, A. R. Piola, C. A. E. Garcia, M. M. Mata, and C. R. McClain (2006), Seasonal and interannual variability of calcite in the vicinity of the Patagonian shelf break (38°S–52°S), *Geophys. Res. Lett.*, 33, L16610, doi:10.1029/2006GL026592.

### 1. Introduction

[2] The Patagonian shelf off Argentina shows complex dynamic processes influenced by tides, the confluence of Brazil and Malvinas (Falkland) Currents, and the transition zone between the shelf water of various origins and the Malvinas Current waters. The Patagonian Shelf tides constitute one of the strongest regimes in the world, where a significant amount of global tidal energy is dissipated by the effect of bottom friction [Glorioso and Flather, 1997]. Strong vertical mixing is promoted by very energetic tidal currents, which in turn create shelf fronts associated with high chlorophyll concentrations visible by ocean color satellites [Romero *et al.*, 2006; Saraceno *et al.*, 2005]. The Brazil/Malvinas Confluence (BMC) near 39°S results from the collision of the southward Brazil Current (BC) with the Malvinas Current (MC), which is a northward

branch of the Antarctic Circumpolar Current (ACC). The MC transports cold and relatively fresh sub-Antarctic waters equatorward, and the BMC generates one of the most energetic regions of the world ocean [Piola and Matano, 2001]. The MC is steered by the topography of the shelf break forming a distinct oceanographic front. High phytoplankton biomass associated with the shelf-break front is attributed to nutrient input by upwelling processes [Carreto *et al.*, 1995].

[3] Previous remote sensing studies associated the Patagonian shelf-break front with occurrence of coccolithophores [Brown and Podesta, 1997]. Early phytoplankton samplings in the area reported the presence of the species *Emiliania huxleyi* [Hentschel, 1932]. More recently, Gayoso [1995] reported relatively high concentrations of *Emiliania huxleyi* in the northern portion of the shelf, near the La Plata River mouth. The key environmental and ecological factors controlling the blooms of these organisms are particularly illumination, mixed layer depth, and photoadaptation. Blooms of *Emiliania huxleyi* have been reported from many regions around the globe [Iglesias-Rodríguez *et al.*, 2002], especially in the North Atlantic [Balch *et al.*, 1989; Holligan *et al.*, 1993a, 1993b]. A review of the literature on the occurrence of *E. huxleyi* and environmental factors [Smyth *et al.*, 2004; Tyrrell and Merico, 2004] reveals that they are associated with highly stratified water, with mixed layers almost always  $\leq 30$  m, indicating a high light requirement. Concerning nutrients, this species seems to tolerate and grow well under low levels of phosphate (high N:P ratios) [Townsend *et al.*, 1994; Tyrrell and Taylor, 1995], presumably due to their ability to use dissolved organic phosphorus. Silicate levels can also be low during *E. huxleyi* blooms, as many times they follow diatom blooms [Heimdal *et al.*, 1994; Holligan *et al.*, 1993a, 1993b]. Oceanic strains of this species have also been shown to tolerate low concentrations of iron [Brand, 1991].

[4] In this paper we offer an analysis of the timing and duration of coccolithophore blooms along the Patagonian shelf break, as well as insights on the mechanisms that drive and maintain these blooms. Our analysis is based on time series of chlorophyll and calcite concentrations derived from satellite ocean color data, historical hydrographic data, and other ancillary satellite data. The percent of coccolithophore bloom pixels were detected in the study region using coccolithophore spectral thresholds that provided excellent agreement with the calcite concentration variability. Therefore, we used increases in calcite concentration as a proxy for coccolithophore blooms. In November 2004 we carried out a cruise along the high chlorophyll band in the Patagonian shelf-break to determine the phytoplankton species composition, primary production rates and the main ocean-

<sup>1</sup>Science Applications International Corporation, Beltsville, Maryland, USA.

<sup>2</sup>Department of Oceanography, Federal University of Rio Grande, Rio Grande, Brazil.

<sup>3</sup>Servicio de Hidrografía Naval and Universidad de Buenos Aires, Buenos Aires, Argentina.

<sup>4</sup>Department of Physics, Federal University of Rio Grande, Rio Grande, Brazil.

<sup>5</sup>NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

ographic and optical features associated with the bloom in spring. A preliminary analysis of the cruise data was performed and used to provide further insights to this study.

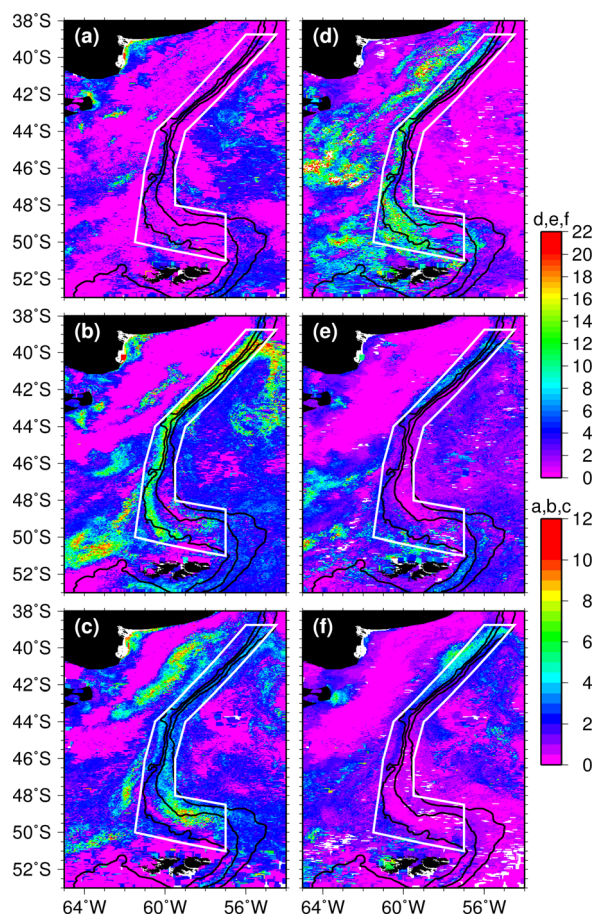
## 2. Data Sources and Methodology

[5] The calcite and chlorophyll-*a* time series were generated separately in two processing steps using different sets of algorithms, but both using the 4-km Sea-viewing Wide Field-of-view Sensor (SeaWiFS) global area coverage (GAC) L1A data. The calcite images were derived using the two-band algorithm for suspended calcium carbonate (also known as particulate inorganic carbon (PIC)), based on normalized water-leaving radiance (nLw) at 440 and 550 nm [Balch *et al.*, 2005; Gordon *et al.*, 2001]. The Chl *a* was obtained from nLws (443, 490, 510, and 555 nm) using the OC4v4 chlorophyll algorithm [O'Reilly *et al.*, 2000] and revised thresholds for coccolithophore masking (C. Brown, personal communication, 2006), which provide more accurate detection of coccolithophore presence. Eight-day and monthly composites were made by binning the L2 SeaWiFS products. The percent of pixels detected by the coccolithophore flag were also binned and used in conjunction with the calcite concentration time series to provide independent evidence of coccolithophore presence. Because the OC4v4 algorithm will produce spurious chlorophyll values when coccolithophore shells are present, the binning of the chlorophyll product was obtained by excluding pixels for which coccolithophores were flagged. This process precludes the estimation of presumably lower levels of chlorophyll associated with the coccolithophore blooms. To our knowledge, there is no methodology available to quantify the possible bias that is introduced to the chlorophyll concentration.

[6] The SeaWiFS time series covers the period of September 1997–October 2005, while the Advanced Very High Resolution Radiometer (AVHRR) sea-surface temperature (SST) data spans from January 1997 to December 2004. Time series of photosynthetic available radiation (PAR) were obtained using the PAR SeaWiFS algorithm [Frouin *et al.*, 1989; Patt *et al.*, 2003], and SST was obtained from monthly 4-km AVHRR Pathfinder grids from the Jet Propulsion Laboratory PODAAC. Monthly climatologies of SST, sea-surface salinity (SSS), and nutrients ( $\text{NO}_3$ ,  $\text{PO}_4$ , and  $\text{SiO}_2$ ) were obtained from the World Ocean Atlas 2001 [Conkright *et al.*, 2002]. Monthly mixed layer depth (MLD) climatology was obtained from the Climatological Atlas of the World Ocean [Levitus, 1982]. Monthly climatologies of Chl *a*, PIC, PAR, and SST were made from the available satellite products.

## 4. Summary and Conclusions

[11] We described environmental processes that drive the timing and duration of coccolithophore blooms along the Patagonian shelf break. The seasonal variability of these blooms responds to light intensity and nutrient supply changes within the mixed layer, which is in agreement with previous investigations in other locations. The early spring bloom is presumably diatom-dominated and starts in September under nutrient-rich upwelled Malvinas waters when the mixed layer begins to shallow (<80 m), and peaks



**Figure 1.** SeaWiFS-derived monthly composites of (a–c) calcite (in  $\text{mmol C/m}^3$ ) and (d–f) chlorophyll (in  $\text{mg/m}^3$ ) for November (Figures 1a and 1d), December 2004 (Figures 1b and 1e), and January 2005 (Figures 1c and 1f). The white polygon delimits the regional domain of study and the black contours correspond to the 200, 500, and 1000 m isobaths.

around November when the MLD is less than 40 m. At this time the phytoplankton community is composed mainly of diatoms and dinoflagellates. After nutrients are depleted from the spring uptake, a coccolithophore bloom begins in November when the MLD is less than 40 m, and peaks in January when the MLD reaches its minimum (18 m) and PAR reaches its maximum intensity. This finding is consistent with earlier studies that identify maximum coccolithophore growth under well-illuminated shallow MLD and low phosphate concentrations, which are environmental conditions that limit the growth of diatoms and other groups.

[12] Although the ocean color data shows that the timing and location of the Patagonian shelf break bloom is very predictable from year to year, significant interannual variability was identified on the intensity of the bloom. Further oceanographic cruises are planned to investigate the causes of this interannual variability. We anticipate that the degree of vertical stratification, and consequently the availability and proportion of nutrients within the euphotic layer, plays a role on driving the interannual changes.